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ABSTRACT. The basic factors which define the specific properties of millimeter and submillimeter waveband gyrotrons are a decrease in the resonator ohmic quality factor and in the limiting currents of adiabatic electron guns with a reduction in the wavelength. It follows from theoretical estimates and experiments that these factors do not prevent the attainment of high efficiencies (on the order of 30 - 40%) in fundamental cyclotron resonance gyrotrons; however, they significantly lower the efficiency of gryotrons operating at the second harmonic of the cyclotron frequency (up to 6% for $\lambda \lesssim 1$ mm in tubes without regeneration).

1. As has already been noted many times (see, in particular, the review [1]), the physical principle which is the basis for the operation of cyclotron resonance masers (CRM), namely, stimulated emission of excited classical oscillators, permits use of spatially developed electrodynamical systems, which makes instruments of this class extremely promising sources of powerful coherent radiation in the short wavelength part of the super high frequency band (SHF). /1056*

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*Numbers in the margin indicate pagination in the original foreign text.

One of the most effective and, at the same time, sufficiently simple CRM variations is the gyrotron, the basic feature of which is the application of an axially symmetric adiabatic electron gun [2], and a highly selective open resonator with a diffraction power output [3].

Continuous mode gyrotrons were first created in the waveband $\lambda \geqq 5$ mm, while in the band 4 mm $\geqq \lambda \geqq 2$ mm there were only pulsed magnetic field gyrotrons *. However, continuous mode gyrotrons (or long pulse gyrotrons) operating in the band $\lambda > 5$ mm are evidently of the greatest interest. It is here that the advantages of CRM are especially evident in comparison with high power electron SHF generators of other classes.

The distinguishing feature of short wavelength gyrotrons in comparison with their longer wavelength prototypes arises from the fact that when the wavelength is shortened, the relative portion of high frequency power loss in the walls of the resonator increases, and there are more difficulties in obtaining intense electron beams with small velocity scatter using an adiabatic electron gun [4].

These tendencies are illustrated by Table 1, where it is shown how the gyrotron parameters must change with decreasing wavelength in the particular case in which the electron flux intensity, the electric field strength at the cathode, and also the ratios of the /1057 resonator radius and of the mean radius of the electron orbit guiding centers to the wavelength are fixed. Here, Q_{ohm} is the ohmic quality factor of the resonator, D and l are the mean diameter and width of the cathode emitting surface, $\alpha = H_0/H_c$ is the ratio of the magnetic field in the resonator to the magnetic field at the cathode, and I_L, the Langmuir current, is the maximum current of an adiabatic paraxial gun, where the current is limited by the space charge of the electron beam in the injector.

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*The first experiments with gyrotrons in the centimeter and millimeter wave bands were described in the reports of I. I. Anatakov, A. V. Ganonaov, V. A. Gintsburg, A. L. Gol'denberg, D. P. Grigor'ev, L. V. Nikolaev, T. B. Pankratova, M. I. Petelin and V. A. Flyagin at the V Inter-University Conference on SHF Electronics (Saratov, 1966).

TABLE 1

Q_{ohm}	D_c, l	α	H_c	I_L
$\lambda^{1/2}$	$\lambda^{2/3}$	$\lambda^{-2/3}$	$\lambda^{-1/3}$	λ

As the wavelength decreases, the ohmic quality factor of the resonator decreases in proportion to $\sqrt{\lambda}$, as follows from Table 1. In order to realize the limiting values of Q_{ohm}, it is necessary to provide increasingly higher purity processing of the internal surface of the resonator. The maximum current of the paraxial adiabatic gun falls off in proportion to λ, despite the fact that the compression of the electron flux, where the compression is characterized by the parameter α, grow, and, correspondingly, the relative (on a scale of λ) dimensions of the cathode are increased.

It is significant that until recent times the selection of electrode configuration for CRM adiabatic guns was accomplished with methods which did not take into account the effect of the field of the space charge of the electron flux on the motion of electrons in the injector. When the currents in such guns exceed 0.1 of the Langmuir current, the velocity scatter becomes so great that is impossible to obtain high efficiency generation.

2. The effects which accompany the decrease in the ohmic quality factor and the electron current with decreasing wavelength are substantially different for gyrotrons at the fundamental cyclotron resonance than for gyrotrons using the second harmonic of the cyclotron frequency. For a gyrotron at the fundamental cyclotron resonance, the optimum (from the point of view of electron energy selection) strength of the high frequency field is relatively small, and in the band $\lambda \gtrsim 1$ mm it can be achieved with currents $I < 0.1\ I_L$ in a resonator with a loaded quality factor significantly less than the ohmic ($Q_{opt} \ll Q_{ohm}$). As a consequence of this, the portion of the high frequency power which is scattered in the walls of the

resonator is small in comparison with the power which reaches the load, i.e., the output efficiency of the instrument is close to the electron efficiency.

In a gyrotron using the second harmonic of the cyclotron frequency, the strength of the high frequency field which corresponds to the maximum electron efficiency has a relatively large magnitude. The resonator quality factor which is necessary for its realization increases with decreasing wavelength and approaches the ohmic quality factor, as a consequence of a drop in the total instrument power, connected with a decrease of the maximum current in the paraxial gun. For waves shorter than a certain critical length (λ_{cr}), having a magnitude of about 4 mm in the pulsed mode*, the condition $Q_{opt} \ll Q_{ohm}$ turns out not to be feasible. On the one hand, this makes it /1058 difficult to attain the maximum electron efficiency, and, on the other hand, it leads to a significant difference between the output efficiency

$$\eta=\eta_{el}\left(1-\frac{Q}{Q_{ohm}}\right)$$

and the electron efficiency η_{el}. For the indicated reasons, the maximum output efficiency of gyrotrons working with the second harmonic of the cyclotron frequency and without using regeneration drops off with decreasing wavelength (for $\lambda < \lambda_{cr}$) in proportion to $\lambda^{3/4}$ (electron beam intensity and the working mode of the gyrotron are assumed to be fixed)**.

3. The properties of short wavelength gyrotrons have been studied experimentally in the band λ = 2.78 - 0.92 mm. A static

*The discrepancy between the values of λ_{cr} presented is caused by a difference in the factors which limit the magnitude of the high frequency field in gyrotrons working in the continuous (overheating of the resonator walls) and pulsed (high frequency breakdown) modes.

**The design features of gyrotrons working at the second harmonic of the cyclotron frequency in the band $\lambda < \lambda_{cr}$ are discussed in detail in the report of T. B. Pankratova and M. I. Petelin at the VII Inter-University Conference on SHF Electronics (Tomsk, 1972).

magnetic field in the gyrotrons is created by superconducting solenoids placed in specially designed crystals (Figure 1). The largest magnitude of the magnetic field is 65 kOe in a cryostat with thermal aperture of 40 mm diameter. The gyrotrons were constructed in sections, and were designed to work with continuous pumping using forced water cooling of the anode, collector, and resonator. The high frequency power goes from the output of the gyrotron to a matched load in the form of a thin-walled quartz cone, cooled with running water. The measurements of the power absorbed by the load, the power lost in the walls of the resonator are carried out with thermocouples which register the temperature of the streams of water which wash the quartz cone and the resonator.

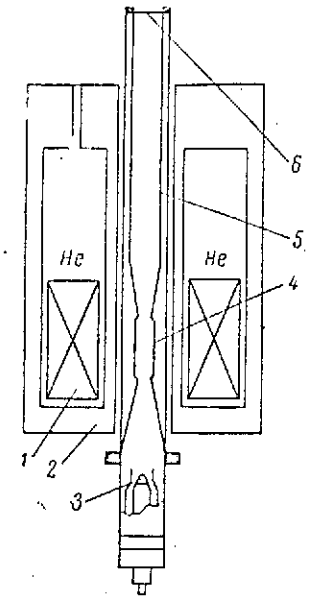

Figure 1. Location of the gyrotron in the cryostat:

1 — solenois; 2 — cryostat; 3 — injector; 4 — resonator; 5 — collector; 6 — high frequency window

The results of the tests of the gyrotrons are summarized in Table 2. The highest output power level $P \simeq 12$ kW at an efficiency of 30% was achieved in continuous mode generation, working at the fundamental cyclotron frequency (working mode H_{021}, $\lambda = 2.78$ mm). The shortest wavelength generation ($\lambda = 0.92$ mm, working mode H_{231}) with output power $P = 1.5$ kW and 6% efficiency was obtained at the second harmonic of the cyclotron frequency. Gyrotrons of both types significantly exceed CRM generators of the same band, described in [5], with respect to output power and efficiency.

In accordance with theoretical concepts, differences are observed in the working of gyrotrons at the fundamental cyclotron resonance, and at the second harmonic of the cyclotron frequency.

TABLE 2. GYROTRON WORKING MODES AND OUTPUT PARAMETERS*

Model no.	Oscillation type	λ, mm	Mode	$n = \frac{\omega}{\omega_H}$	H_0, kOe	U, kV	I, A	P, kW	η, %	η_T, %
1	H_{021}	2,78	cont.	1	40,5	27	1,4	12	31	36
2	H_{031}	1,91	cont.	2	28,9	18	1,4	2,4	9,5	15
	H_{231}	1,95	pulse	2	28,5	26	1,8	7	15	20
3	H_{231}	0,92	cont.	2	60,6	27	0,9	1,5	6,2	5

*Translator's note. Commas in numbers represent decimal points

I, U — current voltage of electron beam
P, η — gyrotron output power and efficiency
η_T — theoretical efficiency for these modes
H_0 — working magnetic field

a) In the gyrotron at the fundamental cyclotron resonance, the maximum output efficiency (35%) was achieved with a comparatively small electron current I = 0.8 A (see Figure 2) when the space charge of the electron flux in the injector is negligibly small, according to the calculation of [6]. The ohmic high frequency power losses in the walls /1059
of the resonator constituted 1/4 of the generator output power. Correspondingly, the electron efficiency (η_{el} = 50%) was close to the output efficiency, and it differed very little from the maximum theoretical value (60%) [6, 7].

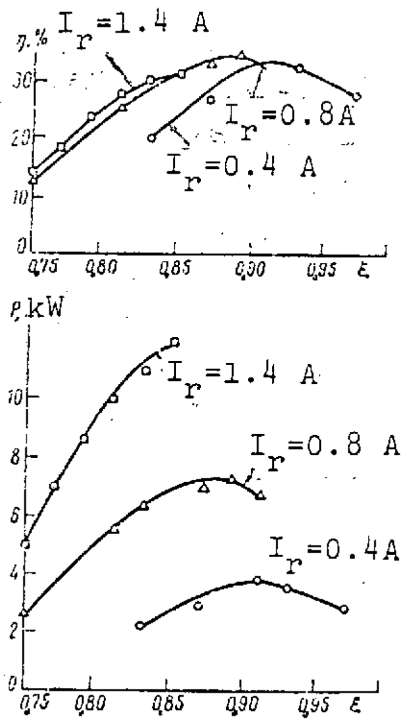

Figure 2. Output power and efficiency as functions of the parameter $\xi = U_a/U_{a\ cr}$ for the mode H_{021}, n = 1, λ = 2.78 mm (ξ is the ratio of the working anode potential to the critical potential)

b) The efficiencies of gyrotrons at the second harmonic frequency were relatively low.

Thus, for example, with λ = 1.9 mm and λ = 0.92 mm, it was 15% and 6%, respectively. In agreement with the calculation, the maximum efficiencies occurred at currents of the order of 0.1 of the Langmuir current, and as already noted, these maxima are upper limits for guns constructed without takeing into account the effect of the field of the beam space charge on the electron velocity scatter (Figure 3a). Because of the boundedness of the current in accordance with the considerations presented earlier, it was necessary to use resonators with diffraction quality factor on the order of the ohmic quality factor, as a consequence of which the high frequency power losses in the resonator walls were close to the output power of the generators (Figure 3b).

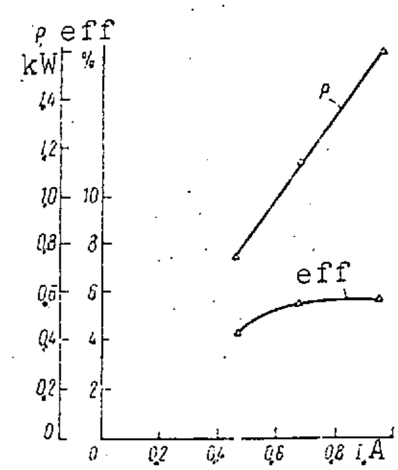

Figure 3. Output power and efficiency as functions of the current (mode H_{231}, n = 2, λ = 0.92 mm)

Experimental values of the output efficiencies as a whole agreed satisfactorily with the values calculated on the basis of [7]; see Table 2. In the calculations, the longitudinal distribution of the high frequency field in the resonator was approximated by a Gaussian function, and the electron translational velocity was assumed to be equal to 2/3 of the rotational velocity. The deviation of the experimental values of the efficiency from those found theoretically can be explained by a scatter in the translational velocities of the electrons, which was of the order of magnitude of the mean electron translational velocity and which changed from mode to mode.

4. The experimental results thus agree with the theoretical concepts and enable one to make the following conclusions concerning the possibility of creating gyrotrons with high efficiency in the millimeter and submillimeter wavebands. /1060

1. Gyrotrons at the fundamental cyclotron resonance with ordinary electrodynamical and electron-optical systems can have efficiency on the order of 30 - 40% in a waveband longer than 1 mm.

2. A significant increase in the efficiency of gyrotrons at the second harmonic of the cyclotron frequency in the short wavelength part of the millimeter and submillimeter wavebands is possible (without the use of regeneration) only with an increase of the electron beam currents. From this point of view, it is advisable to utilize beams working in a mode with large space charge at the cathode, and also beams with an injector placed in a region of nonparaxial magnetic field.

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